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Appendix B: NPEF Tasks

1. Subtask 1 -- Assessment of LightSquared Terrestrial Broadband System Effects on Civil GPS Receivers and GPS-dependent Civil Government Applications

Task Statement

Document LightSquared's Ancillary Terrestrial Component (ATC) and related user equipment signals and antenna specifications and characteristics, GPS receiver specifications and characteristics (e.g., Radionavigation-Satellite Service (RNSS) receiver characteristics submitted to the International Telecommunication Union (ITU)), and future spectrum environment considerations.

LightSquared Ancillary Terrestrial Component (ATC) Technical Parameters

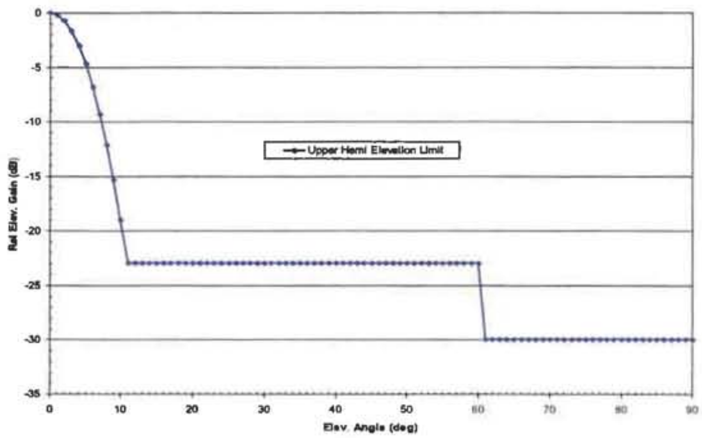
LightSquared plans for three spectrum phases:

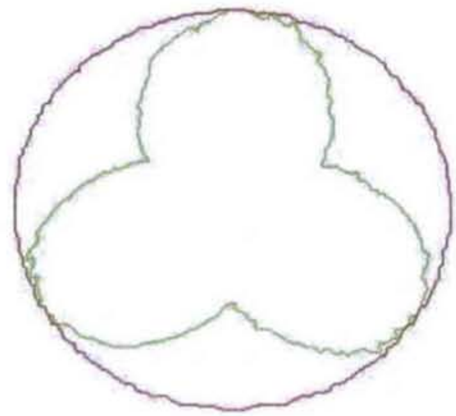
- Phase 0: One 5 MHz channel : 1550.2 MHz- 1555.2 MHz, 62 dBm EIRP per 5 MHz channel
- Phase 1: Two 5 MHz channel : 1526.3 MHz -1531.3 MHz & 1550.2 MHz - 1555.2 MHz, 62 dBm EIRP per 5 MHz channel
- Phase 2: Two 10 MHz channel : 1526 MHz -1536 MHz & 1545.2 MHz - 1555.2 MHz, 62 dBm EIRP per 10 MHz channel

Currently, LightSquared plans to transmit in L-band (1525 MHz -1559 MHz). LightSquared has stated that their intention is to always operate ATCs at least 4 MHz away from the GPS band, at 1559 MHz. Using LTE technology (OFDM, orthogonal frequency division multiplex modulation), each 10 MHz channel will have 1 MHz internal guard band, including 500 KHz on each side of the channel. LightSquared plans to deploy 20W per channel per sector. Each sector will have two transmit chains so a total power of 40W per sector per channel will be transmitted from each base station tower. Given there are three sectors, that results in a total of 120W per tower per channel. In LightSquared plans for spectrum Phases 1 and 2 there will be two channels so the result is 80W per sector or 240W per tower. Further, LightSquared plans to deploy a maximum of 62 dBm EIRP per channel and with two channels per sector, total EIRP per sector will then be 65 dBm per sector. Vertical cross polarization will be used for ATC transmissions.

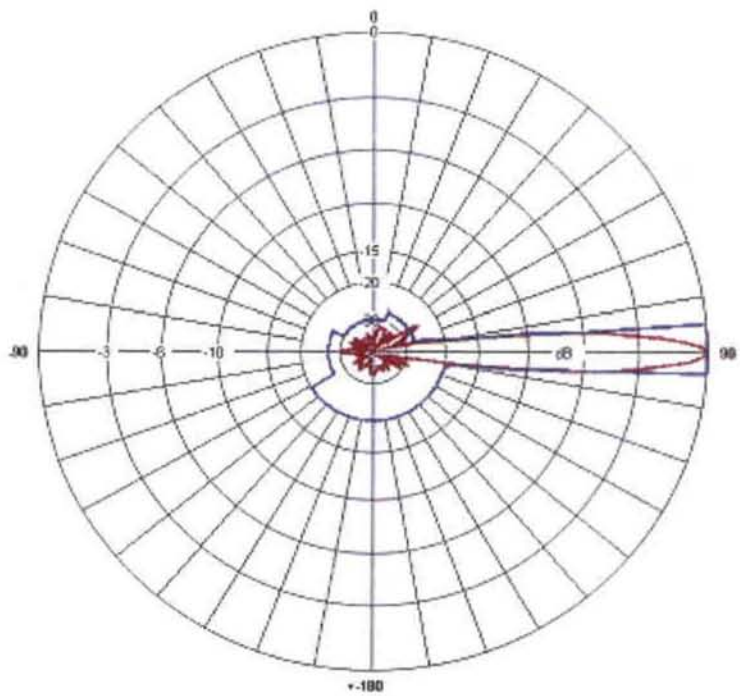
Table 1-1. LightSquared Deployment Phases

Development Phase	Channel Quantity and Size	Channel Locations	Nominal BTS Channel EIRP
Phase 0	One (1) 5MHz FDD	DL 1550.2-1555.2MHz UL 1651.7-1656.7 MHz	32 dBW (25 dBW/MHz)
Phase 1A	Two(2) 5MHz FDD	Channel 1 DL 1526.3-1531.3MHz UL 1627.9-1632.9 MHz Channel 2 DL 1550.2-1555.2 MHz UL 1651.7-1656.7 MHz	32 dBW (25 dBW/MHz)
Phase 2	Two(2) 10 MHz FDD	Channel 1 DL 1526-1536 MHz UL 1627.5-1637.5 MHz Channel 2 DL 1545.2-1555.2 MHz UL 1646.7-1656.7 MHz	32 dBW (22 dBW/MHz)





Rel. Az. Patterns (omni & 3-sector)



Relative Elev. Pattern (~7° beamwidth)
Blue limits = FCC pattern mask

Figure 1-1. ATCt Base Station Transmit Antenna Patterns

ATCt Base Station

- Max. fundamental EIRP: 42 dBW (total in occupied bandwidth)
- Max. unwanted EIRP: -100 dBW/MHz (1559-1610 MHz)
- *Modulation: 4 MSPS RRC QPSK, 5.0 MHz occupied bandwidth
- *Highest carrier freq. 1552.7 MHz
- *Antenna height: 30 m (* from SC-222 WP053)

The distance between transmitters depends on type of morphology around each site as well as other capacity and coverage considerations. LightSquared expects that the distance between transmitters would typically be:

- Dense urban environment: 0.4-0.8 km
- Urban environment: 1-2 km
- Suburban environment: 2-4 km
- Rural environment: 5-8 km

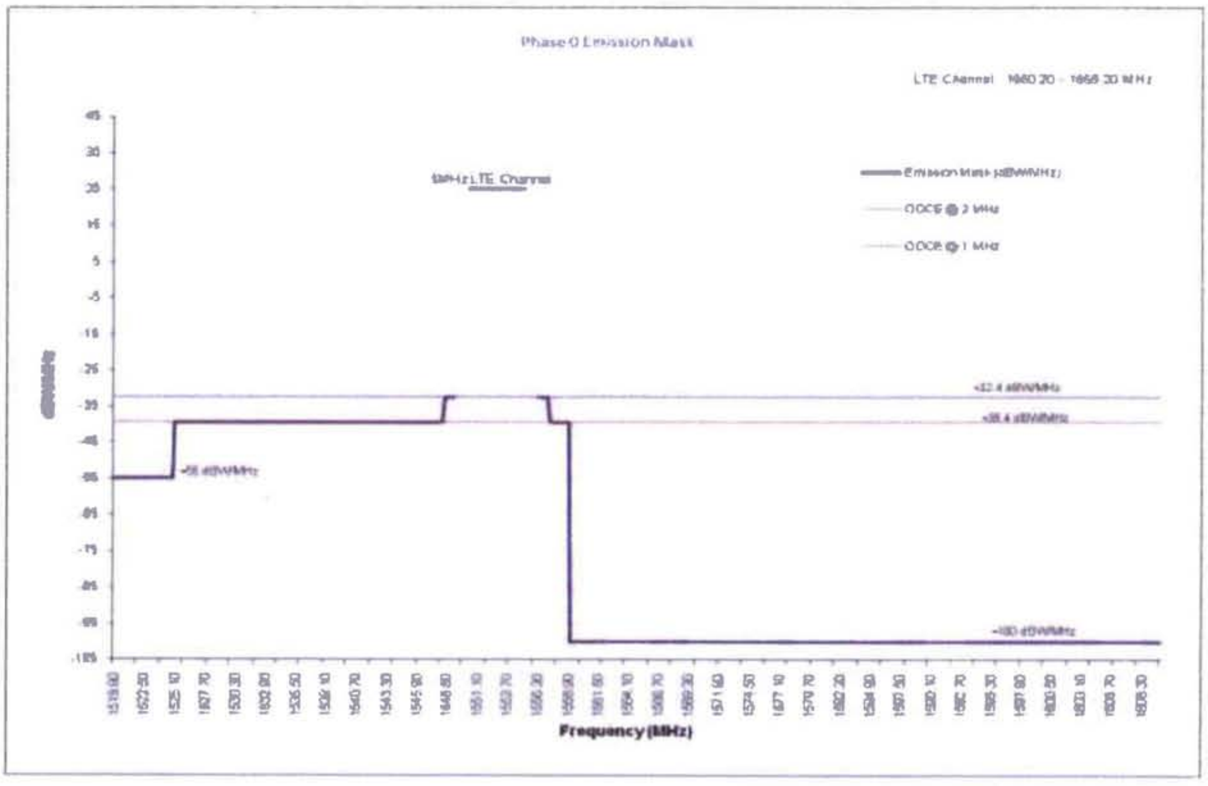


Figure 1-2. LightSquared Planned Spectrum Phases

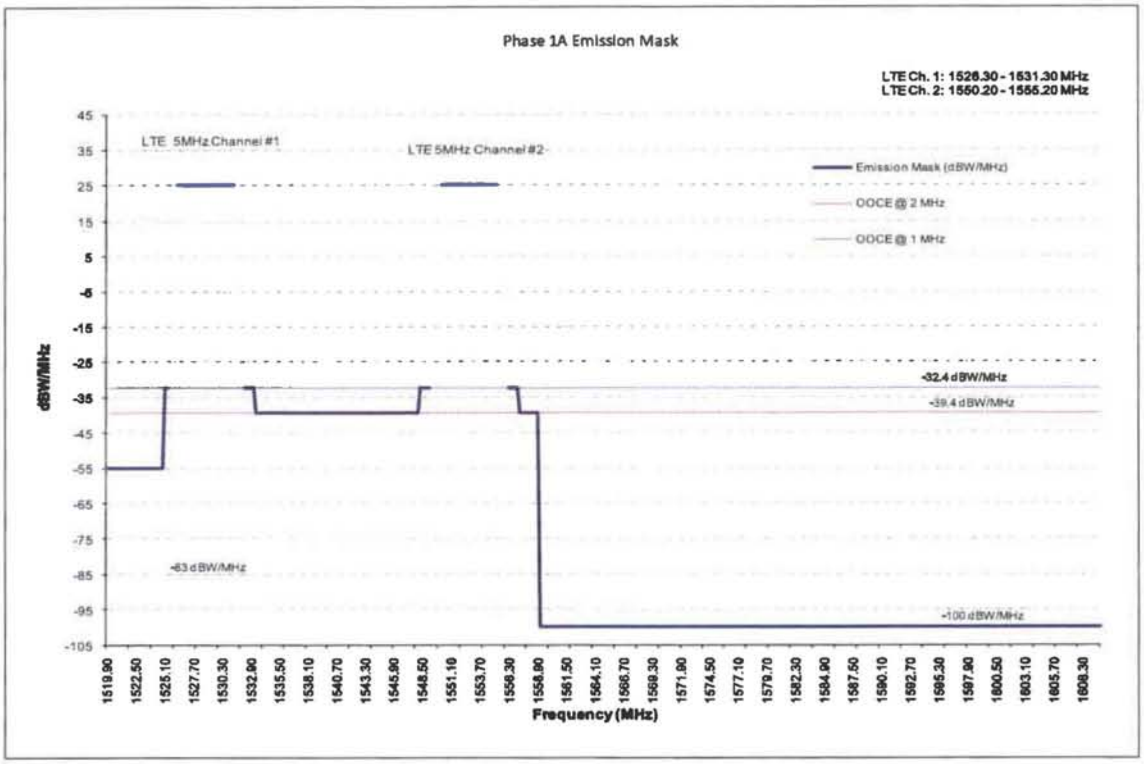


Figure 1-3. LightSquared Planned Phase 1 Base Station Mask

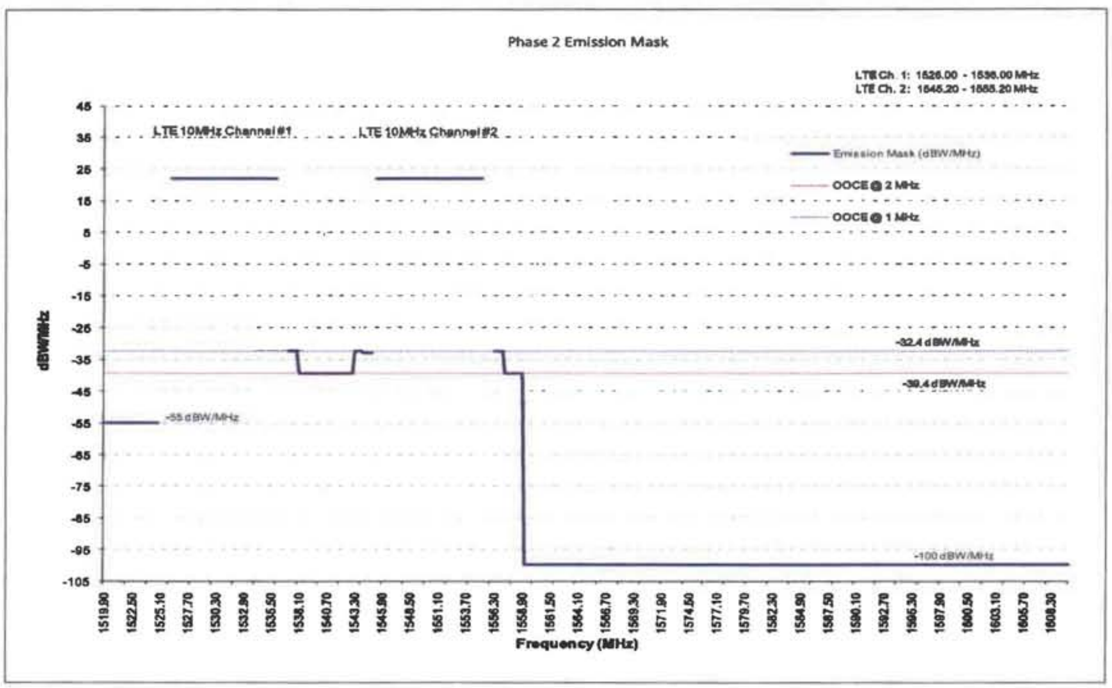


Figure 1-4. LightSquared Planned Phase 2 Base Station Mask

LightSquared User Handset Technical Parameters

When communicating with LightSquared towers, LightSquared mobile devices will transmit in the L-band (1626.5 MHz -1660.5 MHz). LightSquared will use 10% of the total channel bandwidth as a guard band. For example, each 10 MHz channel will have 1 MHz guard band; 500 kHz on each side of the channel. LightSquared anticipates that some future devices may also utilize additional terrestrial cellular bands for transmission, but the specific bands are not yet confirmed. Linear polarization will be used for handset transmissions with a maximum 23 dBm EIRP.

ATCt Mobile Terminal

- Maximum fundamental EIRP: -7 dBW**
- Maximum unwanted EIRP: -90 dBW/MHz (1559-1605 MHz)
- Modulation: LTE (OFDM)**, 5 MHz occupied bandwidth
- Carrier frequency: 1654.2 MHz**
- Antenna height: 1.8 m (est.)

(** from LightSquared RTCA brief (McCall), 10 Feb 2011)

As with the ATC, LightSquared plans three spectrum phases for the deployment of handsets:

- Phase 0: One 5 MHz channel: 1651.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz;
- Phase 1: Two 5 MHz channels: 1627.8 MHz - 1632.8 MHz & 1651.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz; and
- Phase 2: Two 10 MHz channels: 1627.5 MHz - 1637.5 MHz & 1646.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz.

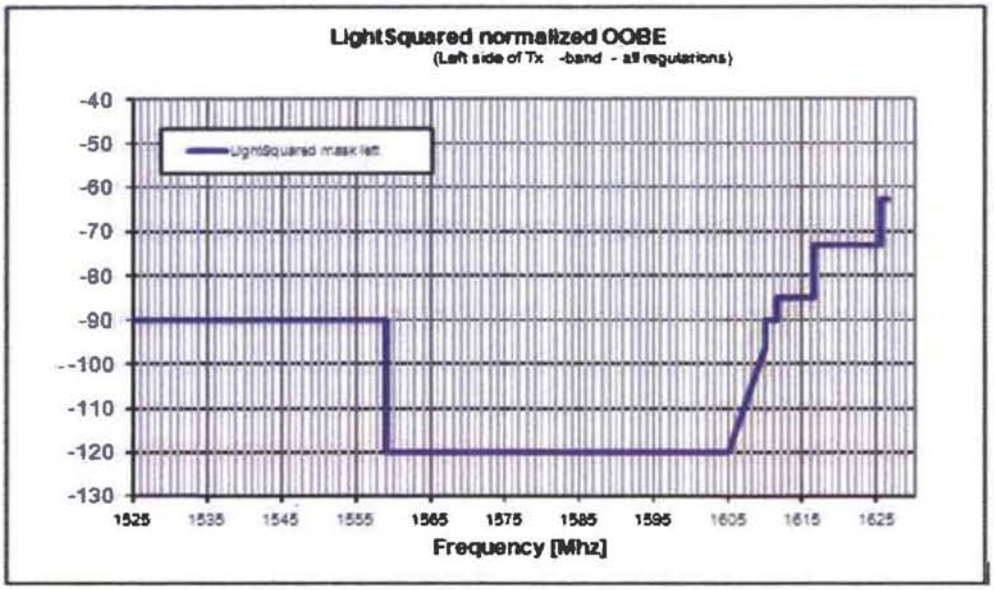


Figure 1-5. LightSquared OOBE Requirements (normalized dBm/Hz left side from 1626.5 MHz for LTE 10 MHz)

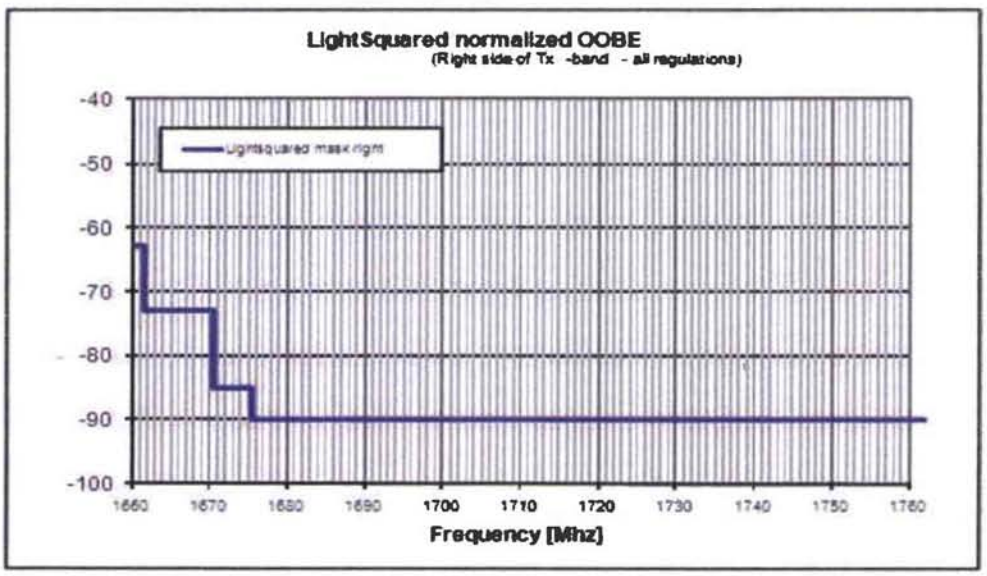


Figure 1-6. LightSquared OOBE Requirements (normalized to dBm/Hz right side from 1660.5 MHz for LTE 10 MHz)

GPS Receiver Specifications and Characteristics

Seven categories of receivers that are representative of the non-military use of GPS in the United States have been identified: aviation, cellular, general location/navigation, high precision, timing, space-based receivers and networks. Each category includes augmented and non-augmented devices. Public safety receivers are included in precision timing and in general location/navigation applications. Receivers used in science are included in the high precision category. Commercial and global maritime distress and safety receivers are included in general location/navigation. Technical characteristics for each of these categories of GPS receivers are provided below.

Aviation

See Appendix 1-A: GNSS Aviation Receivers – Performance Characteristics and Operational Scenarios

Cellular

Baseline Performance Specifications: AGPS receivers in cellular telephones designed for operation with air link technologies covered by the specifications of the 3rd Generation Partnership Project (3GPP), are designed to comply with core performance specification 3GPP TS 25.171. *"Requirements for support of Assisted Global Positioning System (A-GPS) Frequency Division Duplex (FDD)."*

Baseline Conformance Specifications: AGPS receivers designed for operation with airlink technologies covered by the specifications of 3GPP are tested for conformance to test specification 3GPP TS 34.171 *"Terminal conformance specification; Assisted Global Positioning System (A-GPS); Frequency Division Duplex (FDD)."*

GPS Receiver Sensitivity, Assisted Mode: AGPS receiver sensitivity is specified in terms of location accuracy relative to the received signal level. For example, current 3GPP TS 34.171 test requirements call for a location accuracy of 100 meters 95% of the time and a Time to First Fix (TTFF) of between 16 and 20 seconds (the TTFF is dependent upon the specific 3GPP airlink technology supported by the cellular telephone). 3GPP TS 34.171 calls for the cellular telephone to comply with the accuracy metrics listed above at a signal level of -147 dBm and will be tested down to -162 dBm. In addition to 3GPP standards, the TWG will utilize accuracy and availability standards prescribed in the FCC's rules and within OET 71.

GPS Receiver Sensitivity, Unassisted (Autonomous) Mode: Like the assisted mode above, the sensitivity of an unassisted GPS receiver can also be specified in terms of location accuracy. However, neither the 3GPP TS 25.171 core performance specification nor the 3GPP TS 34.171 conformance test specification defines a minimum performance value for this mode. Given sufficient measurement time, an unassisted GPS receiver in a cellular telephone should be able to comply with the accuracy metrics associated with the assisted mode.

General Location/Navigation

Position Accuracy: Dependent upon operational scenario

Velocity: 0.2 meters / second

Acquisition and Tracking Sensitivity: Dependent upon operational scenario

Acquisition Time: 1.0 seconds (Hot Start); 38.0 seconds (Warm Start); 45.0 seconds (Cold Start)

High Precision

Acquisition signals: GPS (L1 C/A, L1C, WAAS L1), (L2 semi-codeless , L2C), (L5, WAAS L5), L-Band (OmniStar, StarFire)

Signal acquisition time (s): TBD

Sensitivity (dBm):

- GPS Point of mean time between cycle slips < 600(s) (usable for RTK)
- GPS Point of loss of lock
- WAAS Point of BER > 1E-6
- WAAS Point of loss of lock
- L-Band Point of BER > 1E-6
- L-Band Point of loss of lock

Precision Timing

Time to "Good Clock" (s):

- Cold: (Position known and fixed, no almanac or time)
- Warm: (Position known and fixed, almanac + (time +/- min))
- Hot: (Position known and fixed, ephemeris + (time +/- us)

Steady state time accuracy: ITU G.810 MTIE, TDEV

Steady state frequency accuracy: ITU G.810 ADEV, MDEV

Phase noise (dBc): TBD

Networks

The performance characteristics of networks vary greatly by network type. This information is still being gathered.

Space-Based Receivers

Measurement precision: The occultation experiment requires the phase rate be measured with 0.8 mm/s accuracy. Data are output at 100 Hz. Typical 1-second measurement precisions are 0.3 mm for the ionospheric error free combination of dual carrier phase measurements. The unknown delay variation through the receiver filters must be less than 1 nanosecond over 0 to 40 degrees C.

Applications: Precision measurements from space orbit, including vertical location of satellites with sub-cm error, use for gravity recovery with integrated K+Ka bands transmit/receive capability, measurement of atmospheric refractivity during GPS limb soundings, ionospheric science measurements of electron content and ionospheric scintillation, ground-based carrier-based frequency transfer.

General description of receiver: Tracks C/A code, L2C code (some receivers), Y1 and Y2 codes using semi-codeless, L5 code (receivers being built now). Receiver can be upgraded in orbit. New software is routinely uploaded after launch. Firmware in FPGAs is modified after launch to add new signal capability.

Observables produced: Time-tagged pseudo-range, carrier phase, and effective C/N_0 are produced for each of the codes mentioned above. Also, the onboard solution consisting of the position, the receiver clock offset (and their time derivatives), along with the satellites used in the solution, the formal error, and the solution Chi-squared are all output.

Appendix 1-A: GNSS Aviation Receivers – Performance Characteristics and Operational Scenarios

1. **Overview**

This appendix describes receiver performance characteristics and operational scenarios for civil aviation applications of GNSS. The focus is on receivers relied upon to allow civilian aircraft to navigate in instrument meteorological conditions (IMC)[1]. These receivers include those installed on aircraft, and those used on the ground for satellite-based or ground-based augmentation systems (SBAS/GBAS).

Currently-available airborne GPS receivers allow civilian aircraft to navigate using GPS for all phases of flight, from en route to precision approach. Over 10,000 GPS-based instrument approach procedures in the United States have been published to date.

2. Airborne Equipment

2.1 Antennas

Minimum performance standards for current-generation airborne GNSS antennas for use in the United States are provided in [1 – 4]. Harmonized requirements are included within the

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[1]GPS is used on many aircraft for other purposes, including photogrammetry and flight test instrumentation. These applications are not addressed here.

International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) [5].

The majority of airborne antennas are active. Some key performance requirements include:

- Passive element gain - The minimum specified gain of the passive antenna component for elevation angles at or above 5 degrees is -5.5 dBic. RTCA recommended installed antenna gain models for minimum and maximum gain for the purposes of interference analysis are provided in [6] and summarized in Figure 1-7 and Figure 1-8 below.
- Axial ratio - Although airborne antennas are nominally right hand circularly polarized, axial ratio is only controlled at boresight (zenith), where it is specified to be less than 3.0 dB. Like most low-profile GNSS antennas, airborne antennas tend to be approximately linearly (vertical) polarized at low elevation angles with typical axial ratios exceeding 15 dB near the horizon.
- Active antenna subassembly gain – at least 26.5 dB from the passive antenna output port to the output port of the active antenna.
- Input 1 dB compression – see Figure 1-9 below for minimum performance, with the level referenced to the output of the passive antenna
- Filtering requirements – see Figure 1-10 for minimum attenuation vs frequency (note that the active antenna is required to provide a 3-dB bandwidth of at least 15 MHz).

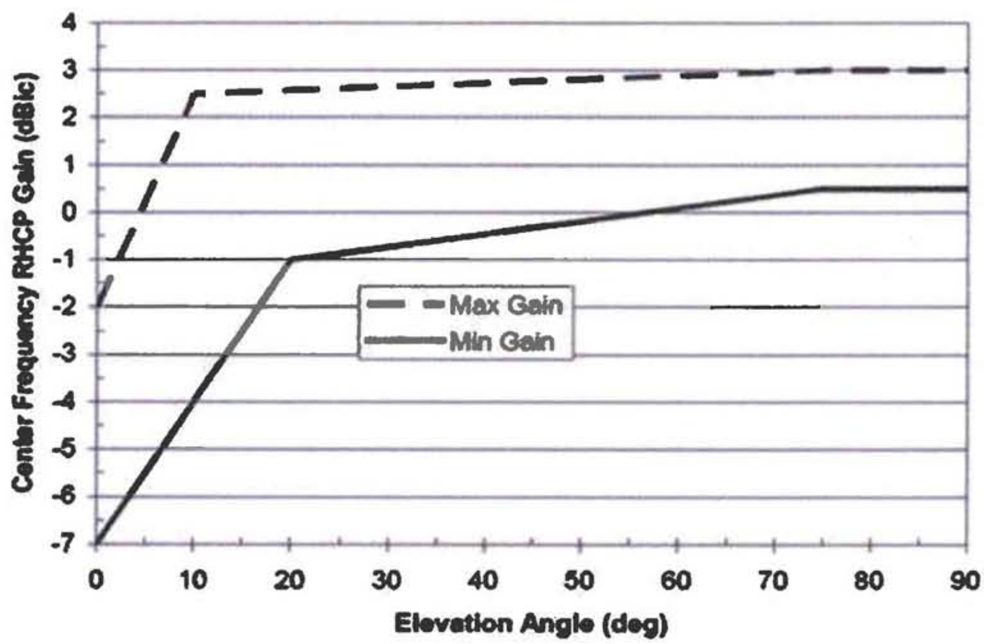

Figure 1-7. Minimum and Maximum Installed Airborne Antenna Gain Above the Horizon

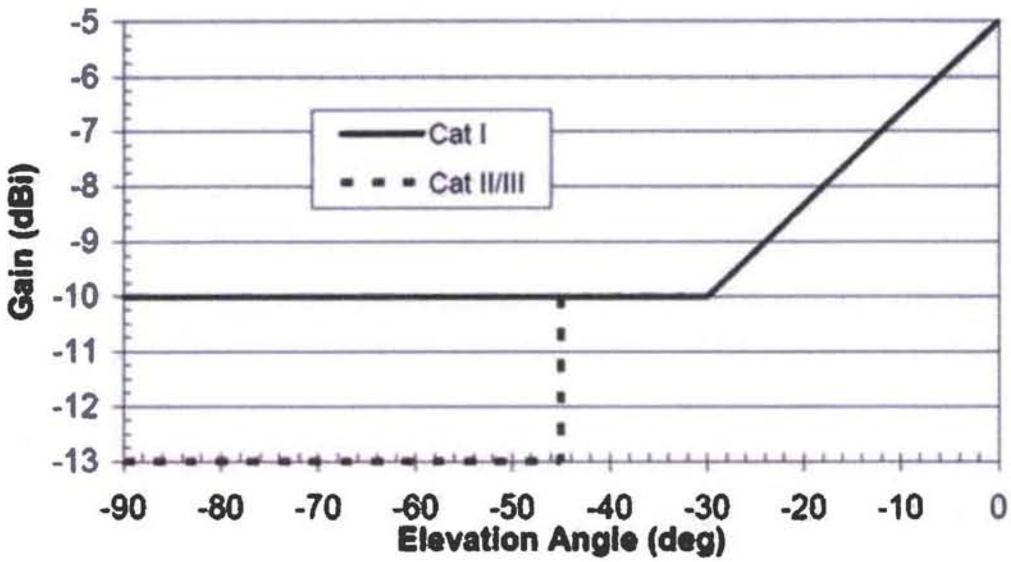

Figure 1-8. Maximum Installed Airborne Antenna Gain Below the Horizon

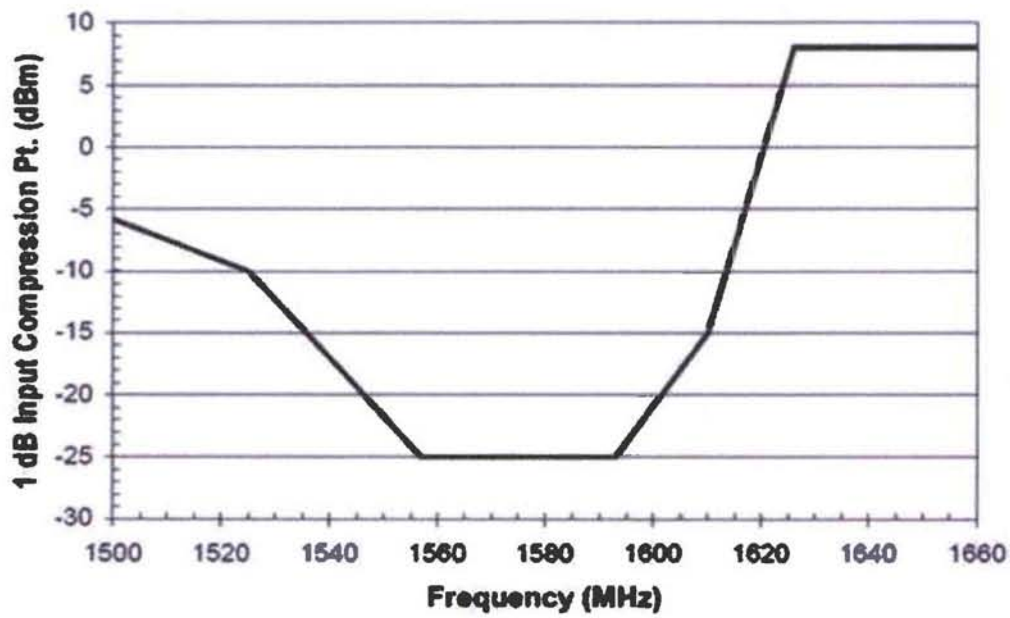

Figure 1-9. Input 1 dB Compression Point for Active Airborne Antenna

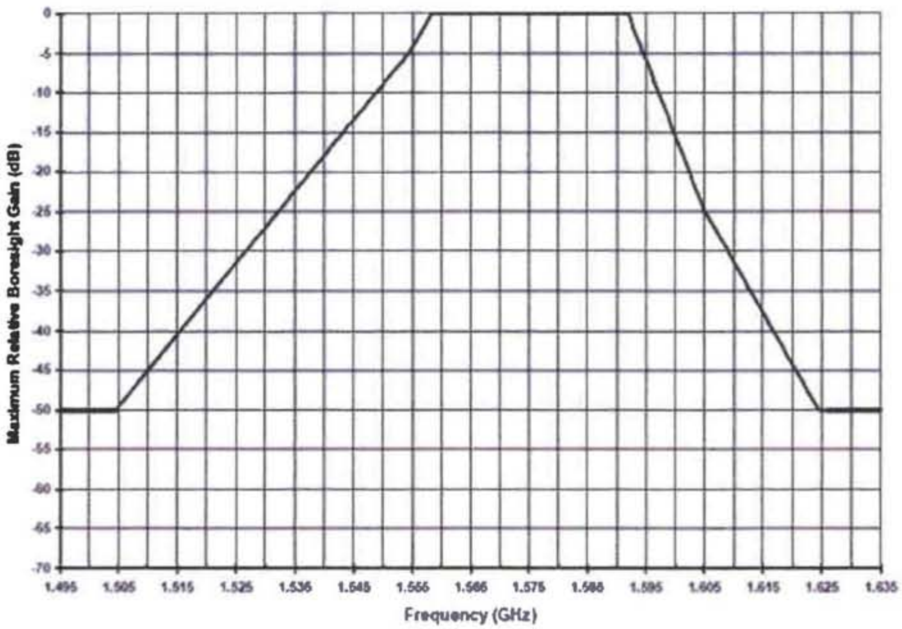

Figure 1-10. Antenna Frequency Selectivity Requirements

To satisfy operational performance requirements, airborne antennas must comply with many other low-level specifications that are too numerous to summarize here. See [3,4]. These include specifications on group delay differential vs. frequency, group delay differential vs. direction of signal arrival, environmental conditions, burnout protection, power supply interfaces. Airborne antennas also must be low-profile. Maximum and minimum cabling losses between the airborne antenna and the receiver would also need to be considered in light of the signal operating environment. A common form factor for airborne GPS antennas is specified in [7]. This form factor calls for a conformal antenna that is $4.7 \times 2.9 \times 0.75$ in^3, with the height dimension (0.75 in) only accounting for the portion of the unit protruding above the fuselage.

2.2 Airborne Receivers

Current-generation civilian airborne receivers used for IMC navigation all rely on the GPS C/A-code signal broadcast at 1575.42 MHz (L1), and typical receivers have 3-dB pre-correlation bandwidths ranging from 2 to 20 MHz. WAAS-capable airborne receivers additionally rely on L1 C/A-like signals that are broadcast by geostationary satellites, which provide differential corrections and integrity data to the aircraft from a ground network. LAAS airborne receivers are provided differential corrections and integrity data from a very high frequency (VHF) datalink.

Well over 100,000 airborne GPS receivers have been sold to date in the United States. Approximately 60,000 of these include both GPS and WAAS functionality. Typical GPS equipment for large air transport aircraft are redundant (two or three) multi-mode receivers (MMRs). These receivers are referred to as multi-mode, because they also provide other navigation sensor functionality (e.g., Instrument Landing System [ILS], very high frequency omnirange [VOR], and marker beacon). They are connected via an aircraft bus to external antennas, flight displays, flight management systems, autopilot, and other avionics that require position, velocity, or timing (PVT) inputs (e.g., automatic dependent surveillance broadcast [ADS-B] equipment and terrain awareness warning systems [TAWS]).

General aviation and business/regional aircraft may include distributed navigation systems similar to those employed by air transport aircraft. However, a more common configuration for general aviation aircraft is the use of a panel mount unit. A typical panel-mount unit integrates GPS/SBAS with ILS/VOR, and VHF communications functionality.

Minimum performance standards for airborne GNSS receivers are provided in [8-11] for standalone airborne equipment, in [12 - 14] for GPS/Wide Area Augmentation System (WAAS) equipment, and in [15, 16] for GPS/Local Area Augmentation System equipment. Performance requirements are far too numerous to describe completely here, so the interested reader is urged to refer to the referenced standards. Some particularly challenging performance requirements include:

- Root-mean-square (RMS) pseudorange measurement error ≤ 15 centimeters at minimum GPS C/A-code signal levels (-128.5 dBm out of a reference 3 dBil user antenna as specified in [17] adjusted by the minimum airborne antenna gain of -5.5 dBic at 5 degree elevation angle as specified in [3, 4]).
- SBAS message loss rate less than 1 message per 1000 at minimum specified SBAS C/A-code signal level. (One SBAS message is 250 bits in length, and the SBAS signal data is sent at 250 bits/second as specified in [14]).

The standards also include detailed test procedures that include laboratory testing with a signal simulator. In the acquisition-reacquisition tests [11,14], only five signals are simulated, and the tests always include one satellite (GPS or WAAS, depending on the specific test) at minimum specified power levels (minimum specified signal-in-space level adjusted by minimum airborne antenna gain at 5 degrees elevation angle). When testing receiver measurement accuracy additional satellites at the minimum satellite power are permitted. However, the measurement accuracy is tested in the pseudorange domain and is *not* dependent on the satellite geometry. It is not permissible to lose track of any satellite during testing, and indeed the quality of the tracking and data demodulation must meet numerous performance requirements including the RMS pseudorange error and SBAS message loss rate requirements described above. See [11, 14, 16] for details.

As with the airborne antennas, requirements for airborne receivers have been harmonized internationally within the ICAO SARPs [5]. A summary of the high-level performance requirements for each phase of flight supported by current generation equipment is provided in Table 1-2. It should be noted that the most challenging requirements are the very stringent integrity levels, which for instance only permit two or fewer occurrences out of 10 million Category I precision approach operations for the GPS sensor to provide position errors exceeding the associated horizontal and alert levels, without an alert to the pilot within 6 seconds.

Table 1-2. ICAO GNSS Performance Requirements

Operation	*Horizontal/ Vertical Accuracy (95%)*	*Integrity Level*	*Horizontal/ Vertical Alert Limit*	*Time-to-alert*	*Continuity*	*Availability*
En-route	3.7 km N/A	$1 - 1\times10^{-7}$ /h	3.7 to 7.4 km N/A	5 min	$1-1\times10^{-4}$/h to $1-1\times10^{-8}$/h	0.99 to 0.99999
Terminal	0.74 km N/A	$1 - 1\times10^{-7}$ /h	1.85 km N/A	15 s	$1-1\times10^{-4}$/h to $1-1\times10^{-8}$/h	0.999 to 0.99999
Non-precision approach	220 m N/A	$1 - 1\times10^{-7}$ /h	556 m N/A	10 s	$1-1\times10^{-4}$/h to $1-1\times10^{-8}$/h	0.99 to 0.99999
Approach with vertical guidance (APV)-I	16 m 20 m	$1 - 2\times10^{-7}$ /approach	40 m 50 m	10 s	$1-8\times10^{-6}$ in any 15 s	0.99 to 0.99999
Approach with vertical guidance (APV)-II	16 m 8 m	$1 - 2\times10^{-7}$ /approach	40 m 20 m	6 s	$1-8\times10^{-6}$ in any 15 s	0.99 to 0.99999
Category I	16 m 4 to 6 m	$1 - 2\times10^{-7}$ /approach	40 m 10 to 35 m	6 s	$1-8\times10^{-6}$ in any 15 s	0.99 to 0.99999

Source: [5]

Airborne equipment are required to meet all of the applicable performance specifications in the presence of interference up to those levels shown in Figure 1-11 for standalone GPS/WAAS, and GPS/LAAS airborne equipment and Figure 1-12 for older airborne supplemental navigation GPS equipment. (Note that these interference levels are system level, i.e., they must be met by the receiver/antenna combination for the installed equipment, and are referenced to the output port of the passive antenna whether the antenna is passive or active). For interference centered at frequencies within the range of 1553.8 – 1593.8 MHz, the maximum tolerable interference levels for standalone GPS, GPS/WAAS and GPS/LAAS avionics specified in [11,14,16] are a function of the bandwidth of the interference (presumed to be noise-like with a rectangular power spectral density). The bottom curve in Figure 1-11 over this range of frequencies is for continuous-wave (CW; i.e., tone) interference, and the top curve in this figure for interference with 1 MHz bandwidth. For interference at center frequencies outside of the range of 1553.8 – 1593.8 MHz, only CW levels are specified.

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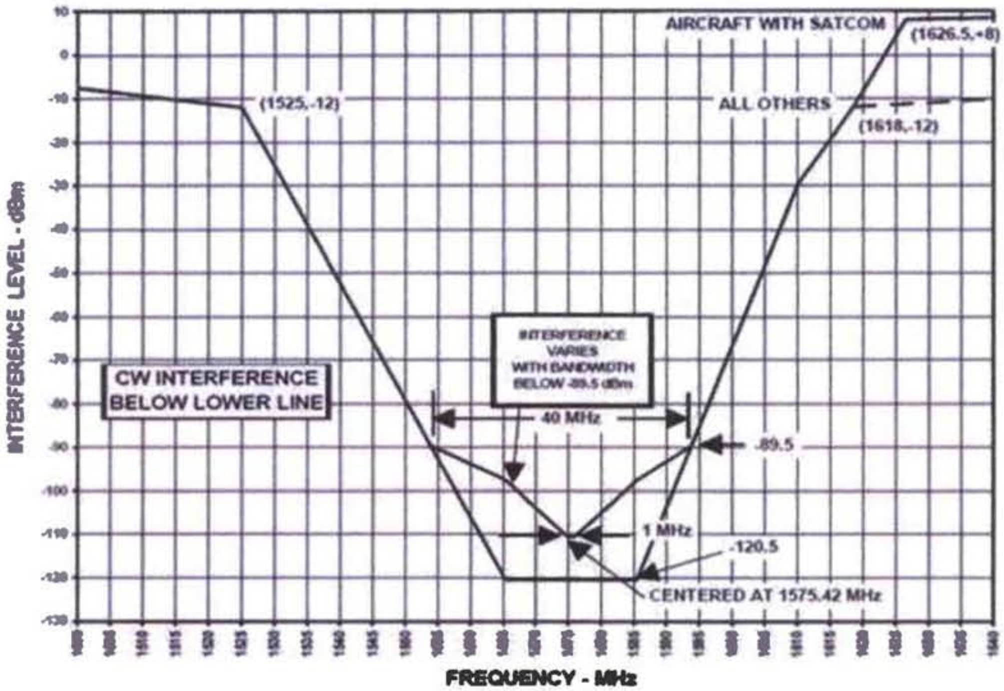

Figure 1-11. Maximum Tolerable Interference Levels for Airborne GPS/WAAS Equipment (referenced to the passive antenna output port)

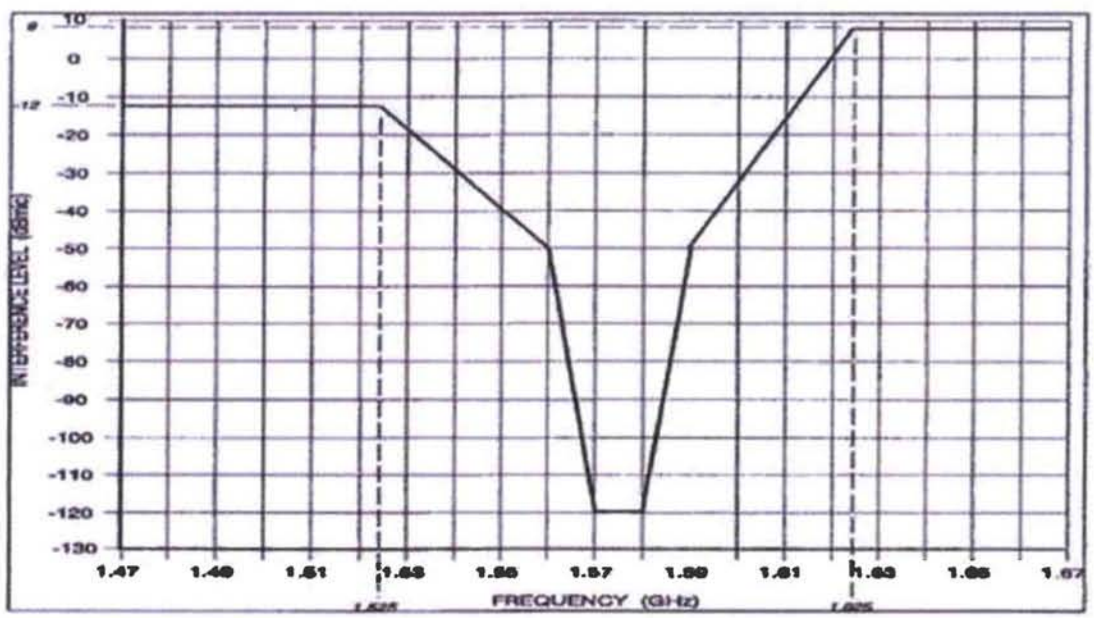

Figure 1-12. Maximum Tolerable CW Interference Levels for Airborne Supplemental Navigation GPS Equipment [8]

2.3 Integrated Equipment

Airborne GPS receivers may be used to provide PVT data to other on-board equipment, including TAWS and ADS-B equipment. Such installations may place additional requirements upon the GPS receiver output.

3. Ground Equipment

To meet the integrity requirements for aircraft navigation, ICAO defines several types of augmentations. Aircraft-based augmentation systems (ABAS) include methods to provide integrity using redundant GPS measurements (i.e., receiver autonomous integrity monitoring [RAIM]) or other on-board sensors (e.g., inertial, barometer-altimeter). The other types of augmentation require GPS receivers on the ground in conjunction with processing facilities to generate differential corrections and integrity data to be supplied to the aircraft. Satellite-based Augmentation Systems (SBAS) provide this functionality using a ground network with GPS receivers widely dispersed over a large geographic region. Ground-based augmentation systems (GBAS) provide this functionality using redundant GPS receivers located on an airport.

GPS receivers are used also for timing purposes for critical Federal Aviation Administration systems.

3.1 WAAS Network

The U.S. SBAS program is referred to as WAAS. The WAAS is a safety critical system that augments GPS by providing additional ranging with geostationary earth orbit (GEO) satellites, improved accuracy with differential corrections, and safety with integrity monitoring. The WAAS system consists of 38 reference stations, three master stations, and six Ground uplink Subsystems supporting three L1/L5 GEO satellites. WAAS Reference Stations (WRSs) are located throughout the Continental United States, Hawaii, Alaska, and Puerto Rico and internationally with stations in Mexico and Canada. Reference stations are located primarily at FAA Air traffic control facilities but some are located at flight service stations, airports and for remote stations in specially constructed shelters. The WRSs utilize the Omni directional NW2225 antenna and G-II reference receiver. Each of the redundant WRS receivers includes the capability to track the GPS and SBAS L1 C/A-code signals and additionally the GPS L1 and L2 P(Y)-code signals using semi-codeless processing techniques. Further details on this equipment are provided in the next sections.

Ground uplink subsystems used with the WAAS GEOs are located at commercial earth station terminals at Woodbine (Maryland), Brewster (Washington), Littleton (Colorado), Napa (California), Santa Paula (California) and Paumalu (Hawaii). These sites also utilize the NW2225 antenna as well as high gain/high directional antennas for L1 and L5 downlink signals. The L1 signal processing in the GUST receiver is the same as with the G-II reference receiver.

WAAS has been operating since 1998 and has been supporting safety of life operations since 2003. The system, at present, supports en route through category I-equivalent (referred to as "LPV") precision approach operations, see, e.g., [18, 19].

3.1.1 WAAS Antenna Assemblies